Study of Iron in Magnetotactic Bacteria

by

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Bacteria have recently been discovered directing their movements by sensing the earth's magnetic field. They contain arrays of crystals of lodestone or magnetite which they synthesize from iron in the ocean. The discovery of the same type of crystals in the abdomens of honey bees and the brains of homing pigeons suggests that nature is not oblivious to the earth's magnetic field. The biological mechanism for sensing magnetic fields has never been determined. These bacteria are capable of biologically synthesizing highly purified single domain magnets that would be very expensive to produce chemically.

The tiny perfect magnetite crystals made by the bacteria possibly could be utilized in microcircuitry. In addition, because these bacteria are attracted to metal surfaces surrounded by distortions in the earth's magnetic field, they may play a role in ship fouling. The unique physical properties of the single domain ferromagnetic crystals of magnetite produced by these bacteria are being analysed for possible electronic applications. Biochemistry of heavy metal storage could be important in recovering metals from ore and nuclear wastes; this is a continuing research project supported by the Office of Naval Research.

Several species of aquatic bacteria which orient in the earth's magnetic field and swim along magnetic field lines in a preferred direction (magnetotaxis) have been observed in marine and freshwater sediments of the northern hemisphere. Their orientation is due to one or more intracytoplasmic (intracellular) chains of single-domain magnetite particles. These linearly arranged particles impart a net magnetic dipole moment to the bacterium, parallel to the axis of motility. Northern hemisphere magnetotactic bacteria with unidirectional motility swim consistently in the direction of the magnetic field, that is, to the geomagnetic north. This implies that their magnetic dipole is systematically oriented with the north-seeking pole forward. Bacteria from aquatic environments in New Zealand and Australia orient in the earth's magnetic field and when separated from the substrate (bottom) swim along magnetic field lines to the south. This implies that their magnetic dipole is oriented with the south-seeking pole forward. Consequently, both northern- and southern-hemisphere magnetotactic bacteria observed to date migrate downward by swimming along the earth's inclined magnetic field lines. (Figure 1)

Magnetotactic bacteria were first discovered in sediments near Woods Hole, Massachusetts in 1974 by R. P. Blakemore. It was observed that most of these bacteria orient and swim along the magnetic lines toward the North. Reversal of the ambient magnetic field by Helm-

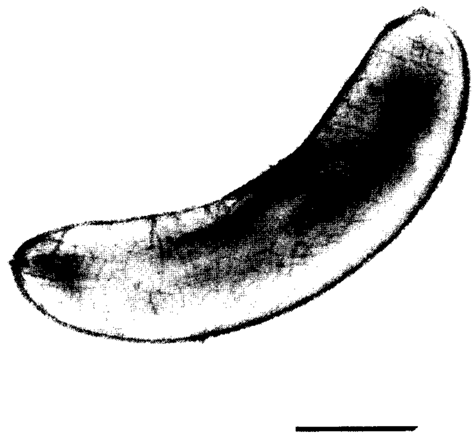

Figure 1: *Negative stain of a magnetic bacterium collected from a fresh water pond. This bacterium was magnified 50,000 times with a transmissiom electron microscope.*
Bar = 1 micrometer

holtz coils caused the cells to make U-turns within one second and swim in the opposite direction. Killed cells also oriented in uniform fields as low as 0.1 G. In these and other respects, the cells behave like single magnetic dipoles.

A magnetotatic spirillum, designated strain MS-1, has been isolated from a freshwater swamp and grown in pure culture (Figure 2). Each magnetotatic cell has an intracytoplasmic chain of approximately 22 iron-rich, electron-opaque particles. Each particle is roughly octahedral, 500 Å along each major axis. Mössbauer spectroscopy of ^{57}Fe in freeze-dried cells shows conclusively that the particles are primarily composed of magnetite, Fe_3O_4. Another iron-containing material with a room temperature Mössbauer spectrum similar to that of the iron-storage protein ferritin is also observed. Thus magnetotaxis is associated with intracellular magnetite. Since the bacteria were grown in chemically-defined media containing soluble (chelated) iron, the

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Figure 2. *Negative stain of magnetic spirillum strain 1. This bacterium was magnified 50,000 times with a transmission electron microscope.*
Bar = 1 micrometer

presence of intracellular magnetite implies a process of bacterial synthesis.

The magnetic properties of magnetite particles depend on their size and shape. For a particle of roughly cubic shape with side dimension d, there is a range of d over which the particle will be a single magnetic domain. The magnetic moment of a single domain is the saturation or maximum magnetic moment of the particle and is unchanging in time. Magnetite particles with dimensions $d \leq 400$ Å are superparamagnetic, that is, thermal activation induces transitions of the magnetic moment between different easy magnetic axis directions with a consequent loss of magnetic "memory." Particles with dimensions $d \geq 800$ Å are multidomain and consequently have macroscopic moments which are either zero or less per unit volume than single domain particles. With d = 500 Å, the magnetite particles in strain MS-1 are within the single domain size range.

Because of strong interparticle interactions, the preferred orientation of the individual particles is such that their axes of magnetization are parallel, north-to-south along the chain direction. Thus, the entire chain acts as a single magnetic dipole with a moment equal to the sum of the particle moments. For a cell containing the average chain length of twenty-two particles, the total moment $M = 1.3 \times 10^{-12}$ emu. In the geomagnetic field of 0.5 G, the total magnetic energy of a cell $MH = 6.6 \times 10^{-13}$ erg. This value is more than an order of magnitude greater than thermal energy, kT (4.1×10^{-14} erg at 300 K). Thus each bacterium contains a sufficient, but not excessive, amount of single-domain-sized magnetite in an appropriate configuration to be oriented in the earth's magnetic field at ambient temperature, i.e., the cell's chain of magnetite crystals functions as a biomagnetic compass.

The simplest hypothesis for the mechanism of magnetotaxis is passive orientation of the bacterium resulting from the torque exerted by the ambient magnetic field in which it swims. Since most magnetotactic bacteria from the northern hemisphere are observed to swim northward, the compass in these cells must have a fixed orientation with respect to the flagellum (tail), with the north-seeking pole opposite to the flagellum. This orientation could be preserved in cell division if the com-

Figure 3. *Phase-Contrast Microphotograph showing alignment of swimming cells of strain MS-1 in an artificial magnetic field. Note accumulation of cells on the side nearest the magnetic pole. Magnified 330 X.*

pass is partitioned between the two daughter cells. Subsequently, during magnetite biosynthesis the magnetic moments of nascent magnetite particles at the ends of the pre-existing chains would become oriented along the chain direction by interaction with the chain dipole moment.

Due to the inclination of the earth's magnetic field, magnetotactic bacteria that swim to the north in the northern hemisphere are directed downward at an angle increasing with latitude. It has been suggested that this downward directed motion confers a biological advantage by guiding the bacteria, when dislodged, back to the sediments. On the basis of this hypothesis, magnetotactic bacteria of the southern hemisphere would be expected to swim south in order to reach the bottom. Recently, several morphological types of magnetotactic bacteria have been observed in sediments of Australia and New Zealand. These bacteria indeed swim consistently to the south, hence downward along the earth's inclined magnetic field lines, as hypothesized. As revealed by electron microscopy, they contain internal chains of electron-opaque particles similar to those observed in magnetotactic bacteria from the northern hemisphere. Like their northern-hemisphere counterparts, their magnetic polarity can be permanently reversed and they cannot be demagnetized.

The prevalence of south-seeking magnetotactic bacteria in southern-hemisphere sediments and north-seeking magnetotactic bacteria in the northern hemisphere verifies the hypothesis that downward directed motion is advantageous for, and upward directed motion detrimental to, the survival of these magnetotactic bacteria with unidirectional motility. Magnetotaxis is a reliable means of keeping these microorganisms in or near the bottom sediments. Since particles in the micrometer-size range with densities close to 1.0 tend to remain suspended in water, gravity is virtually inconsequential in determining the vertical distribution of the bacteria. ■

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